Transient Relativistically-Shifted Lines as a Probe of Black Hole Systems

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ABSTRACT

X-ray spectra of Seyfert-type Active Galaxies have revealed a new type of X-ray spectral feature, one which appears to offer important new insight into the black hole system. *XMM* revealed several narrow emission lines redward of Fe Kα in NGC 3516. Since that discovery in NGC 3516, the phenomenon has been observed in other Seyfert galaxies, e.g. NGC 7314 and ESO 198-G24. We present new evidence for a redshifted Fe line in *XMM* spectra of Mrk 766. These data reveal the first evidence for a significant shift in the energy of a redshift Fe line, the shift occurs over just a few tens of kiloseconds. This shift may be interpreted as deceleration of ejected gas, the velocity of the material lies just above the escape velocity at the implied radial location of the emitter.

Subject headings: galaxies: active – galaxies: individual (Mrk 766) – accretion: accretion disks – stars: individual (Cygnus X-1)

1. Introduction

Active Galactic Nuclei (AGN) are believed to be powered by accretion of material onto a black hole. UV photons from the disk are thought to be upscattered by relativistic electrons, providing the hard X-ray continuum. These hard X-rays illuminate the disk surface, undergoing photoelectric absorption or Compton scattering. High abundance and fluorescence yield make Fe Kα the strongest line in the X-ray band-pass, emitted via fluorescence or recombination processes between 6 – 7 keV, depending on the ionization-state of the gas. This line is commonly observed in AGN (Nandra et al. 1997) with both narrow and broad components. The former has long been thought to be dominated by contributions from cool material at or beyond the optical broad-line-region while the latter is thought to originate close to the black hole. Lines emitted very close to the black hole will show shifted,

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MOS1 data were taken in timing mode, yielding no spectra. In the 2000 observation pileup hardened the MOS spectra but did not affect the pn data. Thus the MOS data were not used from either observation. Source spectra were extracted from both epochs using circular extraction cells of $\sim 45''$ radii centered on Mrk 766. Background spectra were taken from an offset position close to the source. Source spectra were grouped to have at least 20 counts per spectral bin for fitting using the χ^2 statistic. Response matrices were generated for the source spectra using SASv5.3.
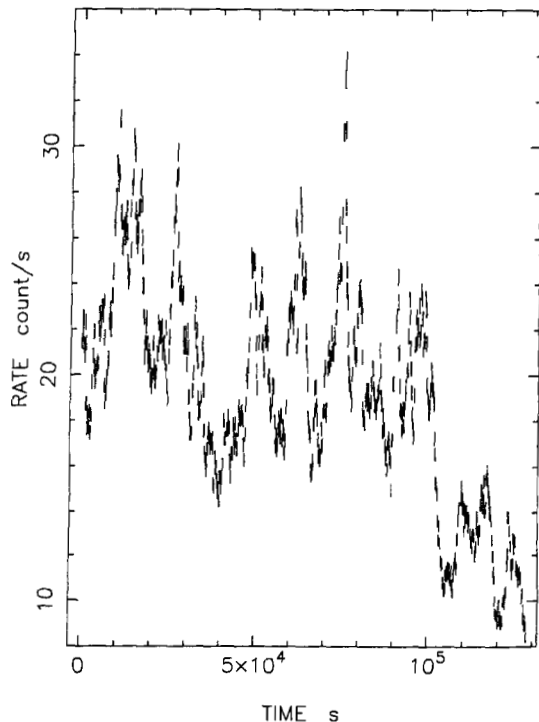

Fig. 1.— *Mrk 766: Light curve from the pn data taken during 2001 May 20-21, accumulated from the source extraction cell in 200 second bins. The high-state corresponds to data from the first 100,000 seconds, and the dip refers to the last 30 ks of the observation where the source flux drops notably.*

Figure 1 shows the light curve from 2001 May, as first presented by Pounds et al. (2003). We confirm the general findings of Pounds et al. (2003) regarding the mean spectrum, i.e. that the spectrum is steep $\Gamma \sim 2.2$ and shows a broad component of Fe Kα at rest-energy ~ 6.7 keV, with a narrower component at 6.4 keV. Our initial spectral fits parameterized the hard X-ray continuum in the 3-11.0 keV range using a powerlaw continuum form, but ignoring data in the 5-7 keV band where the Fe Kα line resides. We assumed a redshift z=0.012929 for Mrk 766 (McMahon et al. 2002).

We also performed time-resolved spectroscopy, accumulating spectra before (high-state) and after (the dip) a drop in source flux (Fig. 1). We adopted the general model of a powerlaw with broad and narrow components to model the complex Fe Kα line which is evident in the
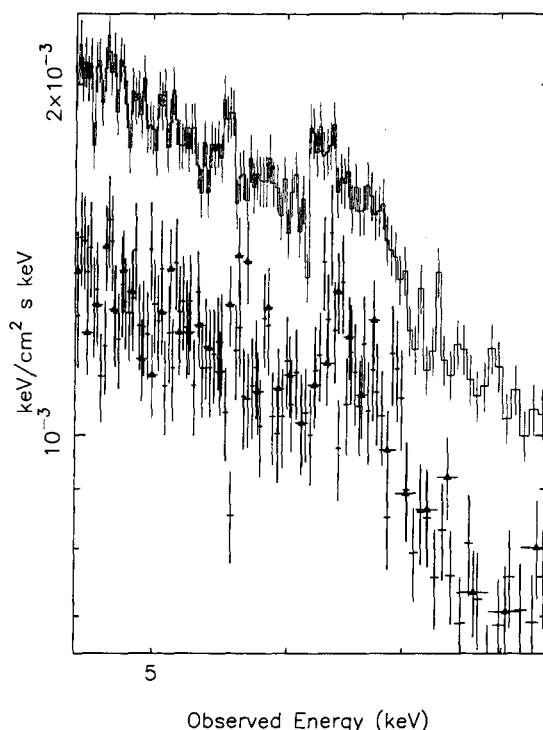
Observed Energy (keV)

Fig. 3.— *Unfolded spectra from two XMM observations of Mrk 766. The top line (green) shows data from the high-state during the long observation of 2001 May 20-21. The red triangles show data from the dip-state of the same observation. A shift is evident in one line from approximately 5.6 keV to 5.75 keV within a few tens of ksec. The black crosses show data from the short observation of 2000 May 2000.*

To further investigate the narrow redshifted lines we examined the significance of features in the Fe Kα regime. We slid a Gaussian model template across data between 3.0 - 11.0 keV, testing for an improvement to the fit at every resolution element, compared to a powerlaw model for the underlying continuum. The background spectrum was subtracted before the test, so features in Figure 4 are attributable to Mrk 766.

In the resulting fit-statistic, $\Delta\chi^2$ of 4.61 represents a feature which is significant at 90% confidence. Fig. 4 shows two different sections of the plot. The left panel illustrates the strong line components, apparently a blend of a broad component from ionized gas and a narrow component from cooler gas. The green line represents the 2001 high-state, the red line 2001 dip data and the black line the 2000 May observation. Fig. 4a suggests there is a shift of the peak energy for the strong line component between the high-state and dip. Parameterizing the line using a broad component plus narrow component fixed at 6.4 keV reveals no significant detection of the neutral component in the dip spectrum. However, the signal-to-noise ratio of the dip spectrum is fairly low, and it is difficult to distinguish photons from the ionized and neutral components of the line. We found the suggestion of
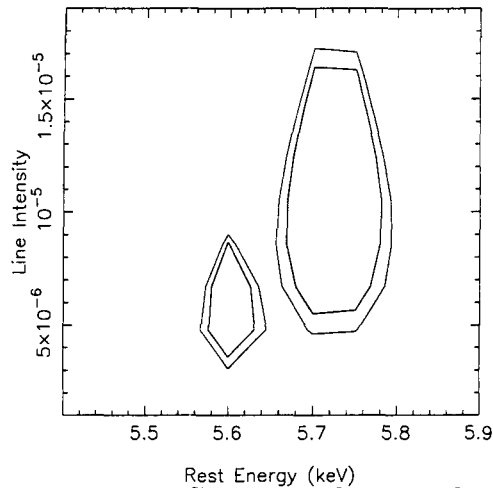
Fig. 5.— *Contours showing the 90% (black) and 95% (red) confidence levels for values of energy and intensity for the line close to 5.6 keV. The left-hand contours are from the high-state and the right-hand contours are from the dip, both from 2001 May.*

3. Discussion

Now several cases of narrow and redshifted lines have been found in Seyfert galaxies and these features may be *a characteristic of black hole systems,* currently detectable only in the relatively bright Seyfert type AGN.

We now review possible physical origins for the observed features. Spallation, which is the breakdown of Fe atoms into lower Z metals by energetic protons, has been disfavored as an explanation of the lines in NGC 3516 (Turner et al. 2002) on the basis of line ratios and rapid line variability. The energy shift detected in the line from Mrk 766 seems inconsistent with the spallation scenario, pushing it further from favor.

In the case of NGC 3516 Turner et al. (2002) discuss an origin from narrow radii which are sporadically illuminated on the surface of the accretion disk. The "Thundercloud" model may be applicable, where the accretion disk is illuminated in patches from magnetic reconnection events (Merloni & Fabian 2001). If the redshifted lines observed in Mrk 766 are red horns of disklines then peak energies in the range 5.6-5.75 keV would occur from a radius $R \sim 30R_g$. For a disk inclined at 30 degrees to our line-of-sight there should be an associated blue horn at ~ 6.7 keV, which would be $\sim 70\%$ stronger than the red horn due to relativistic effects (Fabian et al. 1989, Laor 1991). This is true for both the Schwarzschild and Kerr metrics, which produce similar lines at such radii. If the disk is inclined at 60 degrees then the blue horn would be expected at 7.25 keV at twice the strength of the red horn. Without an independent constraint on disk inclination it is difficult to make a conclusive comment on the consistency of the data with a blue horn. For the case of a disk inclined close to face-on the blue horn would be lost in the broad line component noted by Pounds et al. (2003). While a disk origin remains an interesting possibility, the observation of a rapid energy shift for the emission line in Mrk 766 is suggestive of a decelerating blob of gas, and we explore

time under which the deceleration was observed, and R is the radius at which the material is situated at that time. Assuming the line originates from fairly neutral iron then the implied initial velocity of the emitting blob is 38000 km/s for the line at 5.6 keV in Mrk 766. The observed change in velocity is $\Delta V \sim 7000$ km/s in $\Delta t \sim 65000 s$.

Taking an estimate of the mass of the black hole to be $10^7 M_\odot$ for Mrk 766 (Wandel 2002) yields an estimate of the radius to be $R \sim 3.5 \times 10^{14}$ cm. The escape velocity at this radius is 28000 km/s, close to the (ejection) velocity observed. This ties in nicely with the suggested outflow picture as blobs would have to achieve the escape velocity in order to be ejected and blobs not achieving this velocity would fall back to the disk. Application of the same arguments to the tentative energy shift in NGC 3516 yields a velocity of 47000 km/s, with $\Delta V \sim 9400$ km/s compared to an escape velocity of 41000 km/s at approximately the same radius (and central mass $\sim 2.3 \times 10^7 M_\odot$).

Interestingly, King & Pounds (2003) note that the outflow velocity for the X-ray absorber in PG 1211+143 is close to the escape velocity for that inferred radius, suggesting these are related phenomena, where viewing angle determines whether one sees the ejected gas in emission or absorption. We also note evidence for outflow of gas with velocity $\sim 50,000$ km/s in PDS 456, where Reeves, O'Brien & Ward (2003) estimated a lauch radius of $\sim 40\, R_g$ for the absorbing gas, if the outflow velocity is approximately equal to the escape velocity.

The apparent link between the energy of the redshifted line, and the source flux state during the 2001 observation is intriguing. However, the lack of feature in the earlier observation of 2000 May indicates there is no long-term relation between the line and source luminosity. One possible explanation is that the emitting cloud responds to luminosity changes on short timescales, but that the blobs do not exist on long timescales. This conjures a slightly more complex picture than noted above. The blob may be driven outwards by radiation pressure and maintain a constant velocity so long as that pressure is balanced by gravity. (If this is true, then the infered radius at which the blob exists is smaller than that noted above). If the central source were to switch off completely then a blob travelling below the escape velocity would freely fall back towards the black hole. We observe a factor ~ 2 drop in luminosity which would break the balance between radiation-pressure and gravity, causing the blob to decelerate and the line energy to shift. In this case we initially have gravity balancing the force due to radiation pressure outwards. When the radiation field drops to half the previous value we obtain $\Delta V / \Delta t = GM/2R^2$ yielding $R \sim 1.75 \times 10^{14}$, and escape velocity of 40,000 km/s. In this picture the blob is travelling outwards at a constant velocity approximately equal to the escape velocity. The source flux then drops by a factor 2 and the blob is no longer achieving escape velocity and decelerates. The evolution of the blob then depends on how the central luminosity continues to vary. If the source does not brighten again, the blob will fall back onto the black hole. This picture is appealing, but does not explain why the flux changes *within* the high-state did not show significant line shifts, leaving it unclear whether this picture is indeed more compelling than the simpler case of

AGN where Thomson scattering in the divergent flow redshifts photons to produce the broad red wing observed on the line profile of most AGN. Similar arguments could be applied to produce the narrow redshifted lines observed in NGC 3516, Mrk 766 and other AGN, although in the latter case the rapid shift in line energy may require a more complex explanation than the decelerating emitter, suggested above.

4. Conclusions

Data from several Seyfert galaxies show narrow, redshifted emission most likely explained as Fe Kα lines, shifted by relativistic effects. Mrk 766 provides the first detection of a significant shift in the energy of such a line. The timescale of the shift in line energy is a few tens of kiloseconds, indicating a possible origin in in blobs of gas expelled from the nucleus and then gravitationally decelerated. The nature of the ejection mechanism is unknown at this time, but this may be a newly detectable signature of black hole systems.

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